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Richardson number constraints for the Jupiter and outer planet wind regime

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Abstract. Present theories of the dynamics of the outer planet atmospheres are limited by the absence of direct observations of the wind and temperature layering below their visible cloud decks. We show that if the potential vorticity is assumed to be small at low latitudes, then cloud-tracked wind measurements of the equatorial flow on Jupiter, Saturn, Uranus, and Neptune can be used to constrain their vertical stratification at deeper levels. A Richardson number between 1.2 and 4 is indicated for all the giant planets, which at their rapid rotation implies a much more vertical isentropic structure at these levels than is realized in the terrestrial atmospheres. These conditions signify the likely presence of a unique but as yet unstudied regime for the jovian meteorology, illustrated by a new "Richardson-Rossby" diagram for comparative planetary circulations. The Jupiter case will be directly tested by the Galileo atmospheric entry probe.

Foreword

Voyager imaging measurements of cloud-tracked motions on Jupiter, Saturn, Uranus, and Neptune have revealed low-latitude zonal wind velocities on each of these planets increasing poleward up to the "horns" of their equatorial jets. The associated ratio of the relative to planetary vorticity (comparing the latitudinal shear to the local normal projection of the planetary rotation) is remarkably similar for all four planets (roughly between -1/4 and -1/3). This latitudinal structure contains information about the vertical layering of the jovian atmospheres at levels below those observed by spacecraft remote sensing. By assuming a zero (or plausibly small) potential vorticity over low latitudes, we can use these measured wind profiles to infer a self-consistent Richardson number, a fundamental measure of the vertical stratification and dynamic stability. The distinctive character of the implied dynamical regime remains largely unstudied, and serves as an important point of reference for comparative meteorology.

ZPV Relationships

The stratification of a vertically sheared fluid is usefully characterized in terms of the *Richardson number*, $Ri \equiv [N/(\partial U/\partial z)]^2$ (*cf.* Charney, 1973), where N is the Brunt-Väisälä frequency for buoyant oscillations, U the zonal velocity, and z the geometric height coordinate. For vertically hydrostatic motions (of small vertical-to-horizontal aspect ratio), in an atmosphere with a specific heat and gas constant c_p and R, and a potential temperature $\Theta \equiv T(p_o/p)^{R/c_p}$, also using the log-pressure coordinate $z^* \equiv ln\,(p_o/p)$,

$$Ri = \frac{Re^{-Rz^*/c_p}\,\partial\Theta/\partial z^*}{(\partial U/\partial z^*)^2}. \qquad (1)$$

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For hydrostatic, "gradient-balanced" zonal motion, the vertical wind shear relates to the latitudinal gradient of potential temperature according to the "thermal wind equation"

$$\frac{\partial U}{\partial z^*} = -\frac{Re^{-Rz^*/c_p}\,\partial\Theta/\partial\lambda}{fa(1 + U/\Omega a\cos\lambda)} \qquad (2)$$

where $f \equiv 2\Omega\sin\lambda$ is the planetary vorticity at latitude λ, with Ω and a the planetary rotation frequency and radius. To the extent that this balance is realized, the total Ertel potential vorticity may be expressed in terms of the Richardson number as

$$q = (g/p)\{\zeta + f\,[1 - (1 + U/\Omega a\cos\lambda)\,Ri^{-1}]\}\,\partial\Theta/\partial z^* \qquad (3)$$

where $\zeta \equiv -(a\cos\lambda)^{-1}\partial(U\cos\lambda)/\partial\lambda$ is the vertical component of the relative vorticity of the zonal motion. For a circulation in which viscous and diabatic effects are small, symmetric stability tends to enforce a vanishing q on the equator, as well as the hemispheric coherence of its sign, with $q/f \geq 0$ (Stevens,1983). Other eddy processes, such as baroclinic instability (e.g. Stone, 1966) or wave breaking (Leovy, 1986) will tend to smooth q over latitude or along the isentropes (*cf.* Lindzen, 1990). As noted in our previous study of the Venus/Titan circulation regime (Allison *et al.*,1994), to the extent that the latitudinal variation of the Richardson number can be neglected, this implies a bounding zero potential vorticity (ZPV) envelope for the latitudinal zonal velocity profile of the form

$$U_{max} = (U_e + \Omega a)\,(\cos\lambda)^{2/Ri - 1} - \Omega a\cos\lambda \qquad (3)$$

where U_e is the velocity on the equator. For geostrophic motion ($U << \Omega a\cos\lambda$), as for the jovian planets, (3) implies

$$Ri \approx [1 + \zeta/f - pq/fg\,(\partial\Theta/\partial z^*)]^{-1}, \qquad (5)$$

essentially the same as eqn.(6.2) in Hitchman and Leovy (1986). A *lower limit* on the Richardson number for a stable equatorial circulation may therefore be inferred either from a fit of (4) to a measured latitudinal wind profile or by the evaluation of (5) for $q/f \rightarrow 0$, with

$$Ri_{min} \approx [1 + (\zeta/f)_e]^{-1}, \qquad (6)$$

given some estimate of the relative to planetary vorticity ratio, $(\zeta/f)_e$, on the equator.

The accuracy of this estimate will depend upon the actual increase of q with latitude, and is simply not known *a priori*. But if q is sufficiently well mixed so that $(q/f)_{eqtr} << (q/f)_{Jet}$, the two-point evaluation of (5) for a fixed Ri (and static stability) between the equator and the horns of the jet (where $\zeta/f \approx 0$) would imply $q_{Jet} \approx -(g/p)(\zeta/f)_e(\partial\Theta/\partial z^*)2\Omega\sin\lambda_{Jet}$. Asssuming the (stably monotonic) increase of potential vorticity is crudely bounded below the jet by $q_{max} \sim q_{Jet}\cdot(\lambda/\lambda_{Jet})$, then with the small angle approximation a plausible upper limiting estimate of $pq_{max} \sim -g(\zeta/f)_e f(\partial\Theta/\partial z^*)$ can be used to iterate the evaluation of (5) as

$$Ri_{max} \sim [1 + 2(\zeta/f)_e]^{-1} \approx [2/Ri_{min} - 1]^{-1}, \qquad (7)$$

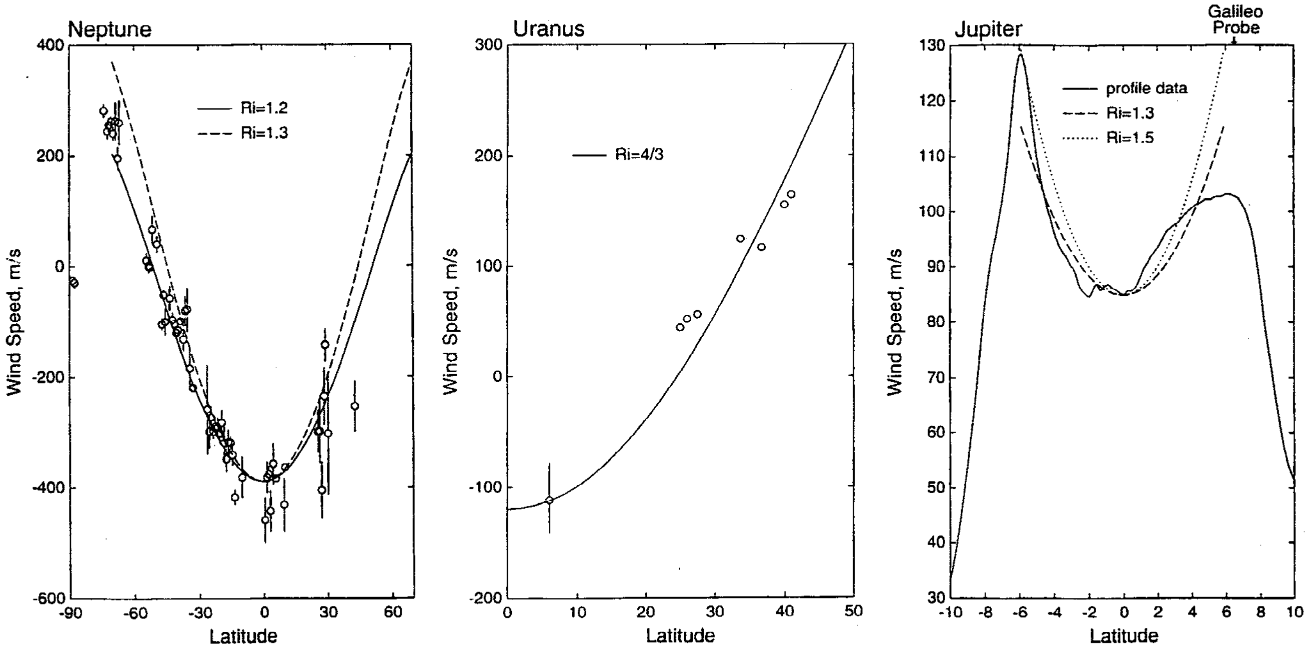

Figure 1. (a) Neptune zonal wind measurements derived from Voyager imaging by Sromovsky *et al.* (1993). The solid curve corresponds to the ZPV profile given by eqn. (4) with Ri = 1.2, the dashed curve to Ri = 1.3. (b) Uranus zonal wind measurements from Voyager imaging between 25 and 45° latitude (Allison *et al.*, 1991), along with one measurement near 5° as inferred from Voyager radio occultation data (Lindal *et al.*, 1987). The solid curve represents a ZPV profile for Ri = 4/3. (c) Voyager wind measurements for Jupiter by Limaye (1986), shown as the solid curve, along with ZPV profiles, dashed and dotted for Ri = 1.3 and 1.5.

provided $-(\zeta/f)_e < 1/2$, with Ri_{min} given by (6). Although not precise, this estimate serves to characterize the stratification realized by an efficiently mixed, low-PV state.

Fig. 1 shows a comparison of the ZPV profiles given by eqn.(4) to the cloud-tracked wind profiles of Neptune, Uranus, and Jupiter. The Neptune case is especially interesting because of the large number of measured vectors over such a wide anticyclonic shear region, extending poleward of 60° latitude. A least-squares fit of (4) to these data gives Ri = 1.2. As illustrated in Fig. 1 (a), ZPV profiles for Ri = 1.2–1.3 provide a good match throughout. Using the polynomial fit of Sromovsky *et al.* (1993), the ratio of the relative to planetary vorticity can also be directly calculated as $-(\zeta/f)_e \approx 0.26$, which with (6) implies a minimum Ri ≈ 1.35 and with (7) $Ri_{max} \sim 2$.

The data for Uranus (Fig. 1b) are extremely sparse, with only seven published cloud-tracked wind vectors below 70° latitude, within the anticyclonic shear zone. The equatorial fit to these data is anchored by one additional but indirect measurement of the wind velocity by the oblateness analysis of Voyager radio occultation measurements. The available data appear to be well-fitted by a ZPV profile with Ri = 4/3, consistent with the value inferred from our least-squares analysis. Allison *et al.* (1991) provide a simple analytic fit to the Uranus wind data implying $-(\zeta/f)_e \approx 0.36$ (but rapidly decreasing toward higher latitudes), giving $Ri_{min} \approx 1.6$ and $Ri_{max} \sim 4$.

Limaye's (1986) digital pattern matching results for Jupiter's equatorial jet are displayed in Fig. 1 (c) in comparison with ZPV profiles for Ri = 1.3 and 1.5. The most discordant feature of the data is the apparent asymmetry about the equator, with zonal velocities at the southward "horn" some 25 $m \cdot s^{-1}$ faster than those to the north. As emphasized by Allison (1990), however, the northern equatorial velocity measurements are likely to be convolved with the relative westward phase drift of the equatorial plumes, which dominate the trackable cloud features at this latitude. Recent Hubble Space Telescope imaging indicates fewer plumes at present and winds some 20 $m \cdot s^{-1}$ stronger than at the time of the Voyager flyby (Beebe, 1995). It therefore seems likely that the relatively good match between the displayed ZPV profiles and the wind data to the south of the equator provides the best estimate of the Richardson number. With $Ri_{min} \approx 1.3 - 1.5$, eqn. (7) implies $Ri_{max} \sim 2 - 3$.

The equatorial wind profile for Saturn is not well resolved and no digitized version of Voyager cloud-tracked vectors is available for this region in the refereed literature. The plotted data by Ingersoll *et al.* (1984) appear to indicate an increase of the zonal velocity from about 436 $m \cdot s^{-1}$ at Saturn's equator to some 494 $m \cdot s^{-1}$ at about 9° latitude. The two-point fit of eqn. (4) to these estimates yields a value of Ri = 1.3 and $Ri_{max} \sim 2$.

The results of these ZPV estimates of the Richardson number for all the giant planets are summarized in Table 1. An order-one value for the Richardson number of Jupiter's deep atmosphere has been previously inferred by Flasar and Gierasch (1986), based on their diagnostic model for the vertical trapping of equatorial mesoscale gravity waves apparent in high-resolution Voyager images. The results presented here are entirely independent and extended to all the jovian atmospheres. The approximate agreement among all four circulation systems is remarkable, in view of the differences in the strength, direction, and width of their equatorial flows. The corroborated order-unity

Table 1. Richardson numbers for the deep jovian atmospheres, based on potential vorticity constraints applied to observed cloud-tracked winds. The vorticity ratios $-(\zeta/f)_e$ indicated in parentheses for Jupiter and Saturn are inferred from the ZPV fits to the zonal wind measurements, while those for Uranus and Neptune are derived from independent analytic fits to the data. The included global Rossby numbers are estimated from peak velocities of the equatorial jets.

	Ri_{ZPV} (eqn. 4)	$-(\zeta/f)_e$ (eqn. 6)	Ri_e (eqn. 6)	Est Ri_{max} (eqn. 7)	Ro_G $U_J/\Omega a$
Jupiter	1.3 – 1.5	(0.33)	–	**~ 3**	**0.01**
Saturn	[1.3]	(0.33)	–	**[~2]**	**0.05**
Uranus	4/3	0.36	1.6	**~ 4**	**0.09**
Neptune	1.2 – 1.3	0.26	1.4	**~ 2**	**0.08**

value for Ri has important but as yet largely neglected implications for the unique character of the jovian regime.

Richardson-Rossby Regimes

Assuming balanced flow (2) and the definition for Ri (1), the ratio of the vertical to latitudinal entropy gradient is given as $[(\partial\Theta/\partial z^*)/(\partial\Theta/\partial\lambda)] = -\mathrm{Ri}\cdot(\partial U/\partial z^*)[fa(1 + U/\Omega a\cos\lambda)]^{-1}$. This implies a scaling relationship for the isentropic slope in the vertical-meridional plane in terms of a global Rossby number, $\mathrm{Ro_G}=U/\Omega a$, measuring the strength of the flow relative to the planetary rotation, and the Richardson number Ri reduced by D*, the depth of the associated motion in scale heights, of the form

$$\Delta_V\Theta/\Delta_H\Theta \sim (\mathrm{Ri}/D^*)(1 + 1/\mathrm{Ro_G})^{-1}. \quad (8)$$

Here $\Delta_V\Theta/\Delta_H\Theta \equiv -[(\partial z^*/\partial\lambda)_\Theta]^{-1}$ denotes the (latitude-vertical) slope of the potential temperature surfaces measured in log-pressure coordinates. (As our choice of symbols suggests, this slope may be estimated as the ratio of the vertical and horizontal potential temperature contrasts over intervals characteristic of the local variations in the scalar field, bearing in mind that these may vary signficiantly with elevation and latitude.) This scaling characterizes the relative effects of the motions on vertical as compared with horizontal heat transport. The observed ensemble of planetary atmospheres suggests that there are at least three different Richardson-Rossby regimes, as illustrated in Fig.2, an extraterrestrial extension of a diagram presented by Phillips (1963).

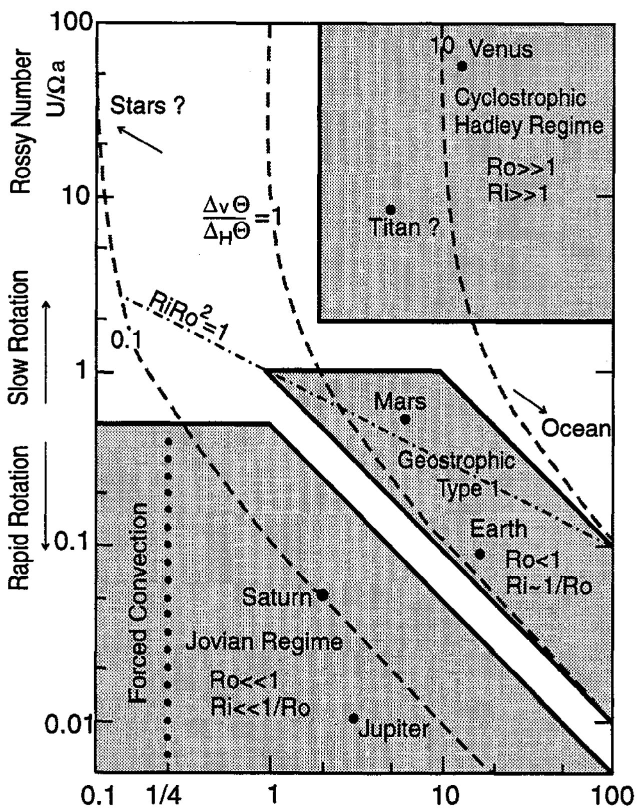

Figure 2. A Richardson-Rossby regime diagram for planetary circulations, showing the schematic boundaries for the jovian, geostrophic (type 1), and cyclostrophic/Hadley regimes. Dashed curves indicate isentropic slopes ($\Delta_V\Theta/\Delta_H\Theta$) of 1/10, 1, and 10. Assignments for Earth, Mars, Venus and Titan are based on measurements of $\Delta_V\Theta/\Delta_H\Theta$ reported by references cited in the text. The diagonal dash-dotted line corresponds to a unitary "Burger number" $B = \mathrm{RiRo}^2=1$, characteristic of the "geostrophic type 1" regime. A "type 2" regime for the interior circulation of the ocean (cf. Phillips, 1963), would lie toward the lower right as indicated, while slowly rotating stars may reside to the upper left.

For global cyclostrophic motion ($\mathrm{Ro_G} >>1$), as observed on Venus and inferred for Titan, eqn. (8) specifies that $\Delta_V\Theta/\Delta_H\Theta$ is essentially the same as Ri/D*, and is likely to be large compared to unity (*cf.* Newman *et al.*, 1984; Flasar and Conrath, 1990). Gierasch (1975) noted that Ri >> D* implies a balance "between adiabatic cooling (due to vertical motion) and radiative heating," along with small horizontal temperature gradients produced by a globally extended Hadley circulation. This regime has now been simulated numerically (Del Genio *et al.*, 1993).

For the *geostrophic* (so-called "type 1") regime exhibited by the general circulation of the Earth's atmosphere, $\mathrm{Ro_G} < 1$, $\Delta_V\Theta/\Delta_H\Theta \sim 1$, and $\mathrm{Ri} \sim 1/\mathrm{Ro_G}$ (with $D^* \sim 1$). In this regime unstable wave motions pump heat both poleward and upward to redress radiative imbalances. Similar conditions are likely present on Mars, but with larger Rossby numbers (Zurek *et al.*, 1992).

For the *jovian regime*, Gierasch (1976) conjectured that Ri<< 1/Ro, noting that this would imply a peculiar meteorology in which the isentropes are significantly more vertical than on the terrestrial planets ($\Delta_V\Theta/\Delta_H\Theta<<1$), as implied by (8) for $D^* \geq 1$. (The isentropes are nearly vertical as scaled by the atmosphere's aspect ratio, though not in the absolute geometric sense.) Our upper bounding estimates of Ri for Jupiter and Saturn, based on eqn. (7), further support the likely realization of this setting in these atmospheres. Although the estimates are not precise, Fig. 2 shows that even several times larger values would lie within the indicated Ri<<1/Ro regime. This implies an effectively two-dimensional motion field, with little horizontal advection of heat, but the details of such a system are still unknown.

Discussion and Interpretation

It is of interest to compare our anticipation of an order unity Richardson number regime on Jupiter with the new results of Ingersoll *et al.* (1995) for the deep static stability, based on their analysis of the observed phase velocity of circular wave fronts excited by the Shoemaker-Levy 9 impacts. According to their analysis, Jupiter's atmosphere must have a large static stability at depth, comparable to the idealized model of Ingersoll *et al.* (1994) with a ten times solar abundant water cloud. Vertical trapping requires a decreased stability aloft of the deep seated wave-guide (*cf.* Allison, 1990) and their calibrated model is equivalent to $NH = [Re^{-Rz^*/cp}\,\partial\Theta/\partial z^*]^{1/2} = 702\ \mathrm{m\cdot s^{-1}}\,p/p_o$ (up to the 450mb level), with p_o an inferred water cloud depth of 20 bars. Presuming a 1 < Ri << 1/Ro regime, with a potential temperature nearly uniform with height, the thermal wind equation vertically integrates as $\partial U/\partial z^* \approx (R/c_p)U\cdot(p/p_o)^{R/cp}[1-(p/p_o)^{R/cp}]^{-1}$ [*cf.* eqns. (38) and (39) of Gierasch (1976)]. With $U\approx 100\ \mathrm{m\cdot s^{-1}}$ (as for Jupiter's equatorial jet) and $R/c_p \approx 0.3$, the implied Richardson number for the idealized stability model becomes $\mathrm{Ri} = (NH)^2/(\partial U/\partial z^*)^2 \approx 557\cdot(p/p_o)^{1.4}[1 - (p/p_o)^{0.3}]^2$. Then for a cloud-tracked wind level at $p \approx 1$ bar and p_o= 20 bars, this implies Ri ≈ 3. (If the nearly vertical isentropic layer does not extend to the full depth of the motion, the Richardson number estimate could be smaller by around a factor of 2.)

Our estimate of an order unity Richardson number and nearly vertical isentropes pertains only to levels with zonal wind profiles similar to the cloud-tracked wind measurements, possibly confined to ~1–3 bars, but as yet unsounded by any direct observations of the thermal structure. At higher levels, near and above the tropopause, the vertical structure is known to be highly stable, Ri is probably large, and the isentropes are nearly horizontal. A second layer of near-horizontal isentropes may also exist at great depth near the base of the water cloud, just above a windless, isentropic interior. By gradient wind balance (2), a vanishing horizontal flow level, if it exists, would imply a vanishing horizontal gradient of potential temperature, consistent with a deep stable layer. The overall potential temperature structure

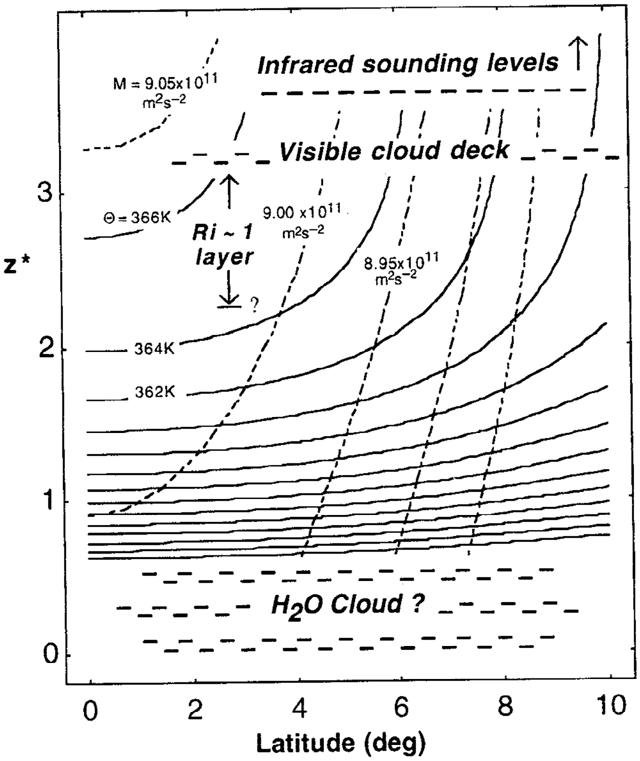

Figure 3. A conjectural picture of the deep potential temperature Θ (solid contours) and specific angular momentum M (dashed) structure of Jupiter's equatorial atmosphere, consistent with an order unity Richardson number and low potential vorticity at levels near or just beneath the visible cloud deck. (Zero potential vorticity obtains wherever the M and Θ surfaces are parallel.) The numbers are only illustrative, with a stability structure approximately consistent with the analysis of SL-9 wavefronts by Ingersoll *et al.* (1995). The actual stratification of the wind layer presumably depends upon Jupiter's deep water abundance.

might resemble that presented by Allison (1994) for Saturn. Fig. 3 shows a similar schematic for the possible deep Θ structure of Jupiter's equatorial region, along with consistently configured contours of specific zonal mean angular momentum $M = \Omega a \cos\lambda(U + \Omega a \cos\lambda)$. This section was constructed assuming a static stability structure similar to that modeled by Ingersoll *et al.* (1994,1995), but with the inclusion of a horizontal potential temperature gradient in geostrophic balance with the cloud-tracked winds. The nearly parallel M and Θ surfaces (where $\nabla\Theta \times \nabla M \approx 0$) below the infrared sounding levels are consistent with approximately zero potential vorticity.

The order-unity value for the Richardson number inferred for levels near Jupiter's cloud deck, although inaccessible to infrared remote sensing, will be directly tested by the Galileo atmospheric probe, with its combined measurements of the vertical profile of the local wind velocity by Doppler radio tracking (Pollack *et al.*, 1992) and the vertical profile of temperature by the Atmospheric Structure Instrument (Seiff and Knight, 1992). While there are no immediate prospects for *in situ* probing of the other jovian atmospheres, it will be of interest to see whether further cloud-tracked wind measurements on Uranus and Neptune from Hubble Telescope can verify our match to eqn.(4) with Ri ≈ 1.3.

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